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13. ABSTRACT (Maximum 200 Words)

We carried out experiments on a structural dynamic model of the twin-tail assembly of the F-15 fighter built by Professor Sathya Hanagud of Georgia Tech. The model was placed on a 250-lb shaker and subjected to a principal parametric excitation. We fixed the excitation amplitude and varied the excitation frequency around 18 Hz. For the same excitation amplitude and frequency, we found five possible responses depending on the initial conditions: (a) very small-amplitude motions of both tails, (b) a large-amplitude motion of the right tail accompanied by a small-amplitude motion of the left tail, (c) a large-amplitude motion of the left tail accompanied by a small-amplitude motion of the right tail, (d) a large-amplitude motion involving both tails moving in phase, and (e) a large-amplitude motion involving both tails moving out-of-phase. The coexisting five responses are the result of the nonlinearities. These results point out some of the shortcomings of testing models with one rigid and one flexible tail or even testing only one tail counting on symmetry. We used nonlinear identification techniques to estimate the linear and nonlinear parameters in a mathematical model of the tail assembly. Then we devised a control methodology to suppress the vibrations of the structural model. Finally, we used the backpropagation-through-time neural controller to suppress its nonlinear responses.

14. SUBJECT TERMS

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Final Technical Report
Alleviation of Buffet on the Twin-Tail
Assemblies of High-Performance
Aircraft
F49620-98-1-0393

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May 1, 1998 - October 31, 2001

Objectives

The fatigue life of the vertical twin tails of high-performance aircraft, such as the F-15 and F-18, is well below what is expected due to buffeting. The buffet loading under some maneuver conditions can cause vertical tail tip deflections of the order of 6 inches, in the frequency range 8.94-39.0 Hz and beyond. The large oscillatory motions are caused by the pressure fluctuations in the wakes emanating from certain upstream components of the aircraft impinging, or nearly impinging, on the tails. The large-amplitude motions can cause one or more of the following problems: (a) Torque box disbond, (b) forward box disbond, (c) loose support fasteners, (d) broken shear tangs, (f) closure disbond, and (g) forward box skin, fitting and closure cracks. Fatigue damage near the 2-in tip pod of an F-15 was reported in 1975, the 2-in pod on a F-15 broke in 1978, and cracks in the 6-in tip pod fitting on an F-15 developed in 1979.

It is known, but not well understood in some cases, that energy can be introduced into a structure by a small-amplitude, high-frequency excitation, and once it is in the structure it can be transferred from high-frequency modes down to low-frequency modes. The danger inherent in such a transformation is that the corresponding motion is transformed from a high-frequency, low-amplitude motion into a low-frequency, high-amplitude motion. In other words, a small-amplitude, high-frequency excitation can excite a large-amplitude, low-frequency response. It is clear that such shifts in the internal energy distributions occur in a very broad class of dynamic systems, including the vertical tails of aircraft. Of course, it is the large amplitude that causes the problems. The large oscillatory motions are responsible for significantly lowering the fatigue life of the tail structures well below what was expected. The excitations are the result of wakes from certain upstream components of the configuration impinging, or nearly impinging, on the tails. The pressure fluctuations in these wakes are what excite the tail structures. Examples of such phenomena have been observed in the VPI&SU Nonlinear Dynamics Laboratory. It does appear that certain structures are much more vulnerable to this transformation of energy than others, and it may very well be that the inherent symmetry of twin-tail structures is a generic characteristic that enhances the transfer of energy from high-frequency to low-frequency modes and hence exacerbates the buffet problem.

The objectives of this project were to investigate theoretically and experimentally the large-amplitude motions of the twin vertical tail assemblies of

high-performance aircraft and develop control strategies to alleviate buffet in these assemblies.

Accomplishments/New Findings

We carried out experiments on a structural dynamic model of the twin-tail assembly of the F-15 fighter built by Professor Sathya Hanagud of Georgia Tech. The model was placed on a 250-lb shaker and subjected to a principal parametric excitation. We fixed the excitation amplitude and varied the excitation frequency around 18 Hz. For the same excitation amplitude and frequency, we found five possible responses depending on the initial conditions: (a) very small-amplitude motions of both tails, (b) a large-amplitude motion of the right tail accompanied by a small-amplitude motion of the left tail, (c) a large-amplitude motion of the left tail accompanied by a small-amplitude motion of the right tail, (d) a large-amplitude motion involving both tails moving in phase, and (e) a large-amplitude motion involving both tails moving out-of-phase. The coexisting five responses are the result of the nonlinearities. These results point out some of the shortcomings of testing models with one rigid and one flexible tail or even testing only one tail counting on symmetry. An interesting phenomenon was observed in the response of the scaled model. Fixing the excitation amplitude and frequency and plucking one tail, we observed that the oscillations of the plucked tail decayed with time and the unplucked tail oscillated with a large amplitude.

We used nonlinear identification techniques to estimate the linear and nonlinear parameters in a mathematical model of the tail assembly. Then we devised a control methodology to suppress the vibrations of the structural model. Finally, we used the backpropagation-through-time neural controller to suppress its nonlinear responses. In the experiments that we conducted the response contains only components with frequencies near the first bending modes and their harmonics. Therefore, we modeled the dynamics of the tails with the following two mass-normalized second-order coupled differential equations:

$$\ddot{u}_1 + \omega_1^2 u_1 = -2\mu_1 \dot{u}_1 - \alpha_1 u_1^3 - \mu_3 \dot{u}_1 |\dot{u}_1| + k(u_2 - u_1) + T_1 \quad (1)$$

$$\ddot{u}_2 + \omega_2^2 u_2 = -2\mu_2 \dot{u}_2 - \alpha_2 u_2^3 - \mu_4 \dot{u}_2 |\dot{u}_2| + k(u_1 - u_2) + T_2 \quad (2)$$

where u_1 and u_2 denote the generalized coordinates of the first bending modes of the two tails and ω_1 and ω_2 are their first linear undamped natural frequencies. For energy dissipation, we incorporated linear and quadratic damping

terms. To account for large deflections, we added a cubic nonlinear term to each oscillator. Also, we included linear coupling terms to account for structural as well as aerodynamic coupling between the tails. Here T_1 and T_2 are the control forces. We used a combination of experimental modal analysis, nonlinear vibration testing, and perturbation methods to identify the linear and nonlinear coefficients in the mathematical model.

We used the method of multiple scales to derive four first-order nonlinear differential equations governing the modulation of the amplitudes and phases of both tails. These equations were used to calculate the steady-state amplitudes and phases as functions of the excitation amplitude and frequency. We estimated the parameters of the model from regressive fits of the experimentally and theoretically determined steady-state response amplitudes. The identified parameters for the right tail are [1] $\zeta_1 = 0.01357$, $\mu_3 = 3.157 \times 10^{-4} \mu \epsilon^{-1}$, $\alpha_1 = -3.675 \times 10^{-2} \frac{1}{s^2 \mu \epsilon^2}$, and $\eta_1 = 161.54 \frac{1}{g s^2}$. The identified parameters for the left tail are $\zeta_2 = 0.01856$, $\mu_4 = 1.958864 \times 10^{-4} \mu \epsilon^{-1}$, $\alpha_2 = -2.977 \times 10^{-3} \frac{1}{s^2 \mu \epsilon^2}$, and $\eta_2 = 275.12 \frac{1}{g s^2}$. Figure 1 shows a good agreement between the theoretically and experimentally obtained force-response curves.

A nonlinear control law based on cubic velocity feedback was used; that is, $T_1 = -G_1 \dot{u}_1^3$ and $T_2 = -G_2 \dot{u}_2^3$. The performance of the control technique was evaluated by comparing the controlled and uncontrolled frequency-response curves. In Figure 2, we show the frequency-response curves of the open- and closed-loop system for both the right and left tails. The response amplitudes depend on the excitation frequency and the initial conditions. The solid lines correspond to stable solutions, whereas the dashed lines correspond to unstable solutions. All of the bifurcations are saddle-node and pitchfork bifurcations. The latter are approximately at the frequencies 19.0 Hz and 21.6 Hz. Curves (a-e) show the responses of both tails as the controller gain is increased. It is clear that, as the controller gain increases, the response amplitudes of both tails decrease. Also, the bandwidth where the different responses occur decreases. For example, it is clear from curve(e) that the different coexisting responses in the frequency range 17.3 Hz to 19 Hz are completely eliminated. Also, all of the dangerous (subcritical) bifurcations are transformed into safe (supercritical) bifurcations; the jumps are eliminated.

Then, we conducted experiments using piezoelectric actuators to validate the theoretical analysis. We forced the twin-tail assembly at 3.1 g and con-

ducted forward and reverse frequency sweeps. The acceleration of the shaker head was monitored, and the input voltage driving the shaker head was adjusted to maintain a constant forcing amplitude. In Figure 3, we show the open- and closed-loop frequency-response curves for the right and left tails for the out-of-phase response. The theoretical and experimental findings indicate that the control law is both an effective vibration suppressor and bifurcation controller [2].

Another means of identification and control of the nonlinear system is through the use of neural networks. In this study, the backpropagation-through-time neural controller (BTTNC) was used in the active control of the F-15 tail section under strong dynamic loadings. Figure 4 displays the results of training the cascaded system. From this figure, it is clear that the neurocontroller suppressed the steady-state vibrations of the two tails [3].

A new strategy, based on the nonlinear phenomenon of saturation, is proposed for controlling the flutter of a wing. The concept is illustrated by means of an example with a rather flexible, high-aspect wing of the type found on such vehicles as HALE aircraft and sailplanes. The wing is modeled structurally as an Euler-Bernoulli beam with inertially coupled bending and twisting motions. A general unsteady nonlinear vortex-lattice technique is used to model the flow around the wing and provide the aerodynamic loads. The structure, the flowing air, and the controller are considered the elements of a single dynamic system, and all of the coupled equations of motion are simultaneously and interactively integrated numerically in the time domain. The results indicate that the aerodynamic nonlinearities alone can be responsible for limit-cycle oscillations and that the saturation controller can effectively suppress the flutter oscillations of the wing when the controller frequency is actively tuned.

Personnel Supported

Students

1. Kreider, W., MS, 1995, "Linear and Nonlinear Vibrations of Buckled Beams"
2. M. Tabaddor, Ph.D., 1996, "Nonlinear Vibration of Beam and Multi-beam Systems"

3. J. Pratt, Ph.D., 1997, "Vibration Control for Chatter Suppression with Application to Boring Bars"
4. R. Krauss, M.S., 1998, "Experimental Identification of Nonlinear Systems"
5. B. Hall, M.S., 1999, "Numerical Simulations of the Aeroelastic Response of an Actively Controlled Flexible Wing"
6. H. Arafat, Ph.D., 1999, "Nonlinear Response of Cantilever Beams"
7. S. Oueini, Ph.D., 1999, "Techniques for Controlling Structural Vibrations"
8. A. El-Badawy, Ph.D., 2000, "Structural Identification and Buffet Alleviation of Twin-Tailed Fighter Aircraft"
9. S. Fahey, Ph.D., 2000, "Parameter Identification of Structural Systems Possessing One or Two Nonlinear Normal Modes"

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4. J. Pratt and A. H. Nayfeh, "Experimental Stability of a Time-Delay System," AIAA Paper No. 96-1643, 37th AIAA/ASME/ASCE/ AHS/ASC Structures, Structural Dynamics, and Materials Conference, Salt Lake City, UT, April 15-17, 1996.

5. C. Chin and A. H. Nayfeh, "Nonlinear Dynamics of Crane Operation at Sea," AIAA Paper No. 96-1485, 37th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Salt Lake City, UT, April 15-17, 1996.
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7. S. S. Oueini and A. H. Nayfeh, "Experimental Implementation of Saturation Control," IUTAM Symposium on Interaction Between Dynamics and Control in Advanced Mechanical Systems, Eindhoven, The Netherlands, April 21-26, 1996.
8. J. Pratt, S. Oueini, and A. H. Nayfeh, "A Terfenol-D Nonlinear Vibration Absorber," SPIE's 4th Annual Symposium on Smart Structures and Materials, San Diego, CA, March 3-6, 1997.
9. H. N. Arafat, A. H. Nayfeh, and C-M. Chin, "Nonlinear Nonplanar Dynamics of Parametrically Excited Cantilever Beams," ASME DETC97/VIB-4028, 16th ASME Biennial Conference on Mechanical Vibration and Noise, Sacramento, CA, September 14-17, 1997.
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25. A. El-Badawy and A. H. Nayfeh, "Control of a Directly Excited Structural Dynamic Model of an F-15 Tail Section," in *Structural Control of the Journal of the Franklin Institute*, Special Issue, 2000.
26. Preidikman, S. and Mook, D., "Time-Domain Simulations of Linear and Nonlinear Aeroelastic Behavior," *Journal of Vibration and Control*, Vol. 6, 2000, pp. 1135-1175.
27. Hall, B. D., Mook, D. T., Nayfeh, A. H., and Preidikman, S., "A Novel Strategy for Suppressing the Flutter Oscillations of Aircraft Wings," *AIAA Journal*, Vol. 39, No. 10, 2001.
28. A. H. Nayfeh, S. A. Emam, S. Preidikman, and D. T. Mook, "An Exact Solution for the Natural Frequencies of Flexible Beams Undergoing Overall Motion," submitted for publication, *Journal of Vibration and Control*.
29. A. H. Nayfeh and W. Faris, "On the Dynamics of Nonlinear thermal Circular Plates," submitted for publication, *Shock and Vibration*.

Presentations

1. M. Tabaddor and A. H. Nayfeh, "Nonlinear Dynamics of a Transversely Excited Flexible Cantilever Beam," ASME 15th Biennial Conference on Mechanical Vibration and Noise, Boston, MA, September 17-21, 1995.
2. K. Oh and A. H. Nayfeh, "Nonlinear Combination Resonances in Cantilever Composite Plates," ASME 15th Biennial Conference on Mechanical Vibration and Noise, Boston, MA, September 17-21, 1995.
3. M. Hajj, A. H. Nayfeh, and P. Popovic, "Identification of Nonlinear Systems Parameters Using Polyspectral Measurements and Analysis," ASME 15th Biennial Conference on Mechanical Vibration and Noise, Boston, MA, September 17-21, 1995.

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6. S. S. Oueini and A. H. Nayfeh, "Control of a System Under Principal Parametric Excitation," The Fourth International Conference on Motion and Vibration Control, Zurich, Switzerland, August 25-28, 1998.
7. A. H. Nayfeh and S. S. Oueini, "Active Nonlinear Vibration Absorber," First ARO Workshop on Novel Structural Damping Concepts and Materials, Virginia Tech, October 19-22, 1998.
8. J. R. Pratt, S. S. Oueini, and A. H. Nayfeh, "Vibration Control using Magnetostrictive Actuators," ASME International Congress and Expo, Anaheim, CA, November 20, 1998.
9. R. Krauss and A. H. Nayfeh, "Comparison of Experimental Identification Techniques for a Nonlinear SDOF System," in *Proceedings of the 17th International Modal Analysis Conference*, Kissimmee, FL, February 8-11, 1999, pp. 1182-1187.
10. A. El-Badawy and A. H. Nayfeh, "Nonlinear Identification of a Scaled Structural Dynamic Model of an F-15 Tail Section," in *Proceedings of the 17th International Modal Analysis Conference*, Kissimmee, FL, February 8-11, 1999, pp. 1175-1181.
11. A. A. El-Badawy and A. H. Nayfeh, Nonlinear Control of a Parametrically Excited Structural Dynamic Model of an F-15 Tail Section, in *Proceedings of the IVth ARO Workshop on Smart Structures*, University Park Campus, PA, 1999.
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13. A. H. Nayfeh, "Can the Practicing Engineer Ignore Nonlinear Phenomena," University of Central Florida, Orlando, FL, February 9, 1999.
14. A. H. Nayfeh, "A Nonlinear Vibration Absorber," University of Pavia, Pavia, Italy, June 5, 1999.
15. A. H. Nayfeh, "Recent Advances and Trends in Nonlinear Dynamics and Control," University TU-Muenchen, Muenchen, Germany, July 6, 1999.
16. A. H. Nayfeh, "The Engineer Grapples with Nonlinear Phenomena," Cornell University, Ithaca, NY, November 2, 1999.
17. A. H. Nayfeh, "The Engineer Grapples with Nonlinear Phenomena," Department of Engineering Science and Mechanics, Virginia Tech, Blacksburg, VA, November 3, 1999.
18. A. H. Nayfeh, "Transfer of Energy from High-Frequency to Low-Frequency Modes," Conference on Mathematics and the 21st Century, Cairo, Egypt, January 15-20, 2000.
19. B. D. Hall, D. T. Mook, A. H. Nayfeh, and S. Preidikman, "A Novel Strategy for Suppressing the Flutter Oscillations of Aircraft Wings," 38th Aerospace Sciences Meeting, AIAA Paper No. 2000-0904, Reno, NV, January 10-13, 2000.
20. A. A. El-Badawy and A. H. Nayfeh, "Identification and Control of a Directly Excited Structural Dynamic Model of an F-15 Tail Section," SPIE's 7th International Symposium on Smart Structures and Materials, March 5-9, 2000, Newport Beach, CA.
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22. S. Preidikman, B. Hall, D. Mook, and A. Nayfeh, "A Nonlinear Numerical Method for Simulating Unsteady Subsonic Aeroelastic Behavior and Evaluating Active, Flutter-Suppressing Control Strategies," Seventh International Congress of Sound and Vibration, Garmisch-Partenkirchen, Germany, July 4-7, 2000.

23. Z. Masoud and A. H. Nayfeh, "Cargo Pendulation Reduction on Ship-Mounted Cranes," Invited Lecture - 3rd International Workshop on Structural Control, Paris, France, July 6-8, 2000.
24. S. Preidikman, B. D. Hall, D. T. Mook, and A. H. Nayfeh, "Nonlinear Modeling of Unsteady Aeroelastic Behavior," IUTAM, Chicago, IL, August 27-September 2, 2000.
25. Z. N. Masoud, A. H. Nayfeh, and D. T. Mook, "Control of Cargo Pendulation for Ship-Mounted Cranes," IUTAM, Chicago, IL, August 27-September 2, 2000.
26. H. N. Arafat and A. H. Nayfeh, "Energy Transfer Between Widely-Spaced In-Plane Bending Modes of Cantilever Beams," IUTAM, Chicago, IL, August 27-September 2, 2000.
27. A. A. El-Badawy and A. H. Nayfeh, "Use of Linear and Nonlinear Vibration Absorbers for Buffet Alleviation of Twin-Tailed Fighter Aircraft," SPIE 8th Annual International Symposium on Smart Structures and Materials, Newport Beach, CA, March 4-8, 2001.
28. S. A. Emam, A. H. Nayfeh, and S. L. Hendricks, "Equations of Motion of an Aircraft Wing Modeled as a Composite Plate-Beam Model Including the Rigid-Body Motion," 18th Biennial ASME Conference on Mechanical Vibrations and Noise, DETC2001/VIB-21563, Pittsburgh, PA, September 9-13, 2001.
29. A. H. Nayfeh and K. Alhazza, "Dynamic Instability and Nonlinear Vibration of Doubly-Curved Cross-Ply Shallow Shells," 18th Biennial ASME Conference on Mechanical Vibrations and Noise, DETC2001/VIB-21410, Pittsburgh, PA, September 9-13, 2001.
30. H. N. Arafat and A. H. Nayfeh, "The Influence of Nonlinear Boundary Conditions on the Nonplanar Autoparametric Responses of an Inextensible Beam," 18th Biennial ASME Conference on Mechanical Vibrations and Noise, DETC2001/VIB-21559, Pittsburgh, PA, September 9-13, 2001.

Interactions/Transitions

We have been communicating with Dr. Mark Hopkins of the Structures Division of the Flight Dynamics Directorate at Wright Laboratory. Dr. Hopkins has included our findings on modal energy extraction in his basic research plans to support current and future developmental research in smart structures.

We have a grant with Cessna Aircraft Company to develop a nonlinear aeroelasticity code that couples the nonlinear dynamics of wings with an unsteady nonlinear aerodynamic model.

Dr. Nayfeh has acted as a consultant with Rohini International on an SBIR Phase II on Buffet Alleviation from the Structures Division of the Flight Dynamics Directorate at Wright Laboratory.

We have developed and delivered to Cessna Aircraft Company a nonlinear aeroelasticity time-domain code that couples the structural dynamics of wings with an unsteady nonlinear aerodynamic model. The aerodynamics of the whole aircraft is modeled. The code predicts flutter and post flutter, including limit cycles.

New Discoveries, Inventions, or Patent Disclosures

None

Honors/Awards

A. H. Nayfeh

1. A. H. Nayfeh, American Institute of Aeronautics and Astronautics Pendray Aerospace Literature Award, 1995

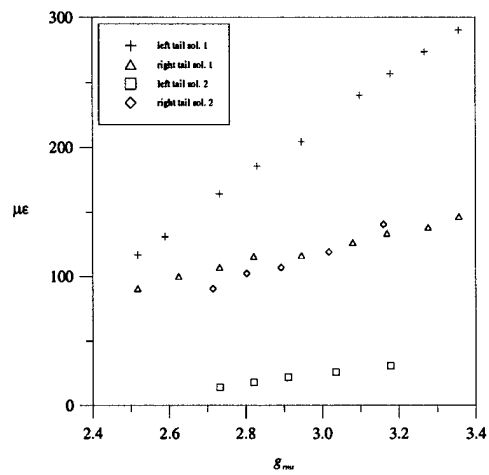
(For seminal contributions to perturbation methods, nonlinear dynamics, acoustics, and boundary-layer transition; praiseworthy for their quality relevance, timeliness, and lasting influence on the aerospace community.

2. Honorary Doctorate, St. Petersburg University, Russia, 1996

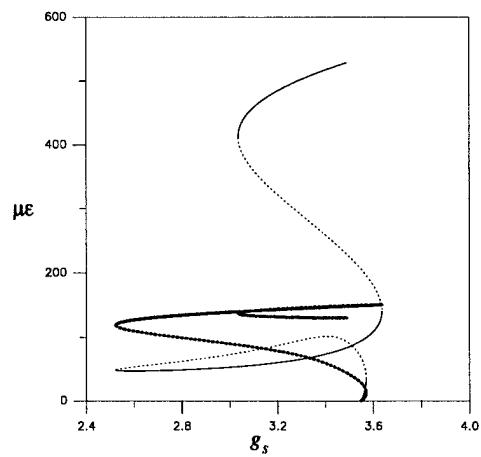
3. American Society of Mechanical Engineers J. P. Den Hartog Award, 1997 (Presented in recognition of lifetime contributions to the teaching and practice of vibration engineering.)
4. Frank J. Maher Award for Excellence in Engineering Education, 1997
5. College of Engineering Dean's Award for Excellence in Research, 1998
6. Honorary Doctorate, Technical University of Munich, Munich, Germany, 1999
7. Fellow of American Institute of Aeronautics and Astronautics, American Academy of Mechanics, American Physical Society, Society of Design and Process Science, and American Society of Mechanical Engineering

D. T. Mook

1. Frank J. Maher Award for Excellence in Engineering Education, 1983
2. American Institute of Aeronautics and Astronautics (Associate Fellow)
3. American Academy of Mechanics (Fellow)
4. American Society of Mechanical Engineers (Fellow)

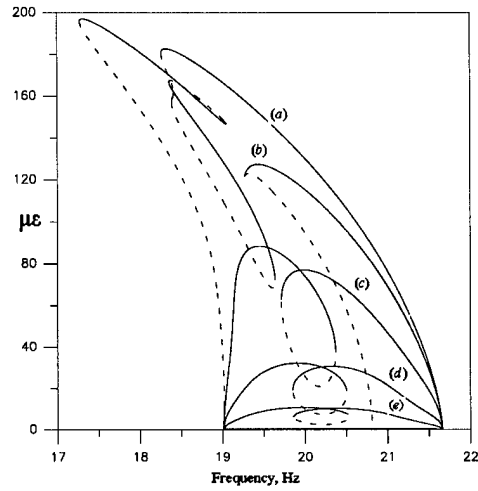


(a)

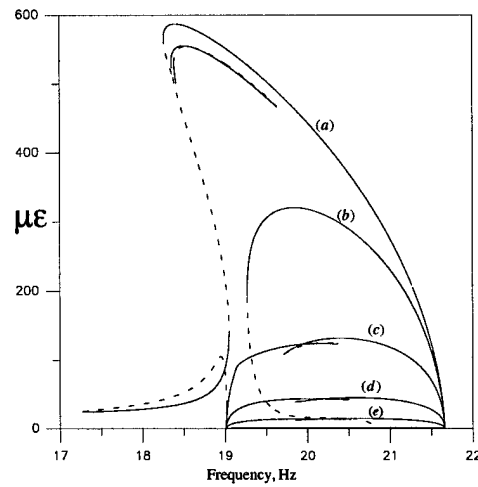


(b)

Figure 1: (a) Experimentally obtained force-response curves at 18.0 Hz. (Forward Sweep) (b) Theoretically obtained amplitude-response curve at 18.0 Hz when $k = 87$ ($1/sec^2$).

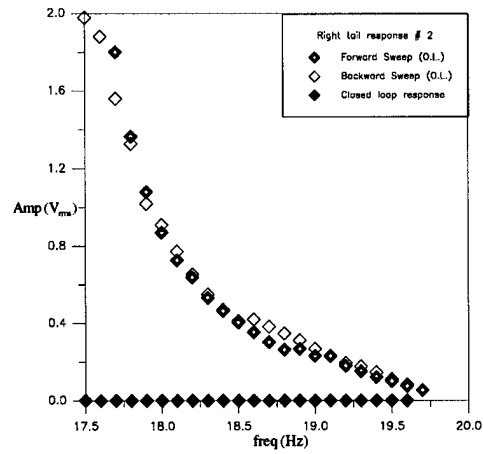


(i) right tail

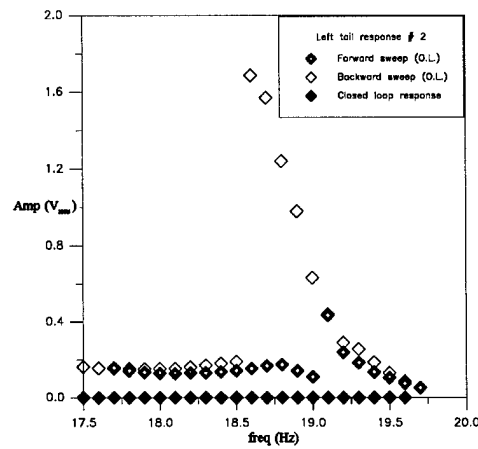


(ii) left tail

Figure 2: Effect of varying the feedback gain on the frequency-response curves of the specified tail ($F=3.2\text{ g}$): a) $G=0$, b) $G=0.01$, c) $G=0.1$, d) $G=1$, e) $G=10$.

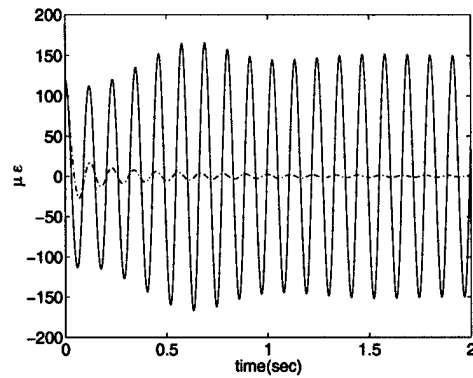


(a) right tail

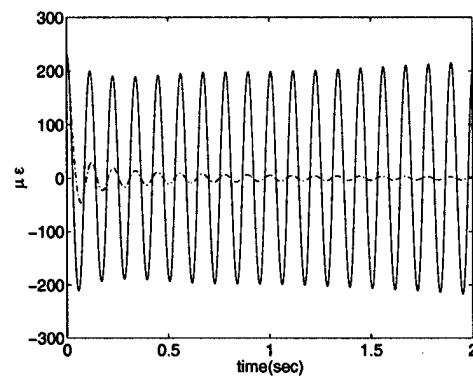


(b) left tail

Figure 3: Frequency-response curves of the out-of-phase responses before and after control.



(a) right tail



(b) left tail

Figure 4: Time histories of the responses of the tails(-) without control and (-.)with control.